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THE PROBLEM OF COLLECTING DIAGNOSTIC INFORMATION UNDER SPACE-FLIGHT CONDITIONS AS ONE OF THE TRENDS IN MEDICAL CYBERNETICS

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ABSTRACT

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The function of the medical data-collecting systems on board spacecrafts is reviewed. Future long-duration flights will require the use of on-board computers and powerful diagnostic algorithms. Author

One of the important problems in modern space medicine is the /1*
collection of diagnostic information which is necessary for making space flights safe. The most recent achievements in science and technology, in the fields of radio electronics, biotelemetry, power engineering, etc. are employed to solve this problem. The development of medical cybernetics has made it possible to formulate several new ideas regarding the collection of diagnostic information under space flight conditions. The purpose of the present article is to examine these ideas.

It should be first pointed out that the system for collecting medical, particularly physiological, information on-board a spacecraft can be

* Note: Numbers in the margin indicate pagination in the original foreign text.

assigned to a number of complex cybernetic systems, to which information is transmitted, received, accumulated, and processed. We shall employ the term "physiological information-measuring system", which stresses the following four leading aspects of the problem: physiological - aimed at solving physiological (medical, diagnostic) problems; measuring - connected with a quantitative determination of physiological processes; information - examines data circulating in the system as control and connection signals; and finally an aspect which underlines the necessity of employing a specially-organized system. The elements of this system would comprise a group of properties for obtaining the maximum amount of information on the physiological condition of the cosmonaut. In a very general /2
form, a physiological information-measuring system may consist of an information source in equipment on-board the spacecraft and on the earth, an information receiver, and communication channels. The term diagnostic information can be used to designate that portion of data coming from the information source (cosmonaut) to the information receiver (doctor), which is processed into decisions and commands which are directly aimed at providing safety during the flight. The time required for the information cycle thus is of the greatest importance - i.e., the time from the moment when the measuring system receives data from the cosmonaut until the moment when the corresponding command is obtained from him or the spacecraft system. It is clear that under space-flight conditions the time required for the information cycle must be minimal. Using the conception of the physiological information-measuring system as a basis, let us examine the following three questions in succession:

- The improvement of systems for collecting diagnostic information with reference to prolonged space-flights;

- The utilization of on-board computers;
- The construction of algorithms for processing information.

During the flights of the Soviet and American cosmonauts, the systems for collecting physiological data were primarily constructed for solving the problems of medical control. The basic problem entailed in collecting the measurement parameters and building the electronic equipment consists of determining the state of the cosmonaut when he is placed in orbit, and of rendering him medical aid if necessary. The problem of selecting more extensive scientific information, which is of interest for forecasting the cosmonaut's reaction and for developing programs for future flight experiments (Ref. 1), can be solved at the same time. However, as far as we are concerned this problem occupies a secondary position. The transition to longer space-flights, which traverse a much greater distance, makes it necessary to regard the second problem on an equal footing with the problem of medical control. The fact is that during a prolonged flight a sufficiently-accurate diagnosis of dangerous deviations in the condition of the cosmonaut cannot be performed only on the basis of data obtained during experiments on earth or on the basis of limited information recorded during the flight. It is necessary that the results derived from the medical studies which are periodically carried out be reprocessed into diagnostic criteria for performing operative medical control. The problems of obtaining information are closely related with the creation of effective diagnostic algorithms.

The development of systems for collecting physiological information during prolonged flights covering great distances necessitates the solution of the following problems:

- The obtaining of a maximum amount of data while employing a minimum amount of equipment;

- The transmission of a maximum amount of data by means of a telemetry channel having a limited capacity; /3

- A decrease in the time required for information processing.

The latter problem arises due to the following two facts: the necessity of rapid decisions in the system of operative medical control and the necessity of rapid coding of extensive scientific data to specific diagnostic criteria which may be employed for augmenting the safety of the flight. The presence of a doctor on the crew of the spacecraft does not simplify this problem, because the training of the doctor, whose possibilities for processing information, and his responsibilities have definite limits (Ref. 2).

The problems entailed in the optimum construction of a system for physiological measurements on-board a space-craft were investigated by ourselves in several works (Ref. 3, 4, 5). One of the new principles advanced was the placement of two independent measurement systems on-board the spacecraft: medical control and medical studies. The system of medical control is a somewhat simplified variation of physiological measurement systems existing at the present time on the spacecraft "Vostok", "Voskhod", "Mercury", and "Gemini". It is designed for recording a small number of data which are sufficient for distinguishing the acute diseases (conditions) which rapidly or suddenly appear, such as shock, collapse, acute cardiovascular insufficientcy, etc. In this case it is necessary to record two to three physiological parameters as continuously as possible - with the future utilization of an intra-cabin telemetry system which will make it possible to perform medical control while the cosmonauts move freely about in the compartment of the spacecraft. The system of medical studies must have a somewhat larger number of channels, since its purpose is to select detailed data on the state of different physiological functions in the cosmonaut's body. However, in view of the limited weight, size, and fuel requirements of equipment on-board the spacecraft, it is difficult to count on retaining the existing principle: each parameter has its own measurement channel. We have formulated the principle of multi-purpose utilization of the channels. This channel can be utilized several times, with various recorders attached to it and, if necessary, changing its technical characteristics. This would make it possible to record 25-50 or more physiological parameters while using 6-8 channels.

It is expedient to record the data in the system of medical studies under special programs, each of which is aimed at studying a definite physiological system in the body. The efficiency of the program is determined both by the selection of parameters, and by the group of functional tests which it includes. Apart from specialized programs, general medical programs can be utilized, whose purpose may be reduced to collecting information on the state of the main body systems: the cardiovascular, respiratory, neuromuscular, and central nervous system. The multi-purpose /4
utilization of the channels, in accordance with the principle of programmed studies, makes it possible to obtain a maximum amount of data with a minimum amount of equipment on-board the spacecraft.

The principles recommended above for constructing the on-board medical apparatus were tested during a flight of the Soviet multi-seated spacecraft

"Voskhod". The medical control was performed by means of a special apparatus designed for continuously recording three indices (electrocardiogram, seismocardiogram, and pneumogram) in each of the three cosmonauts. A special device was employed for medical studies, which made it possible to record four different parameters consecutively on one channel (electroencephalogram, electrooculogram, dynamogram, and the motor movements in writing). These parameters were recorded under an appropriate program which included the requisite functional tests. Experimental data were obtained which contained the effectiveness of the recommended systems of physiological measurement.

An increase in the duration and length of space-flights leads to a significant reduction in the volume of data transmitted to earth from the spacecraft. This is due to the sharp decrease in the transmitting capacity of the telemetry channels. During the flights of the Soviet spacecraft, the possibility of "compressing" the information was employed during transmission on telemetry channels: an "enveloping" phonocardiogram was recorded (Ref. 6), and two parameters were transmitted on one channel (Ref. 7). However, the effective utilization of telemetry channels having limited capacity for transmitting a maximum amount of information is only possible by utilizing on-board computers. Since the cycle of information significantly increases in the "cosmonaut-spacecraft-earth" system as the distance covered by the flight increases, the appearance of on-board computers can already be seen in the near future as a development in space technology. Along with technical problems (orbital calculations, control of life-support systems, automatic orientation, etc.) these devices will solve problems of automatic medical control (Ref. 8, 9, 10). It will also solve problems entailed in the programmed selection of scientific and diagnostic information and the "compression" of data for transmission to the earth along telemetry channels having limited capacity, and for storage on the on-board memory systems. When a doctor is included in the spacecraft crew, an on-board computer can fulfill the role of "a diagnostic machine"-advisor, in addition to automatically signalling dangerous conditions.

A new physiological information-measurement system, which is atonomous with respect to the earth, arises with an on-board computer. Over a period of time, this system is of great importance in providing for the safety of the space-flight, and "earth" keeps for itself only the role of consultant and recorder of scientific information. Studies in the field of on-board computers are of great interest for space medicine. This represents a portion of the extensive, general medical problem of "diagnostic machines". The use of "condition diagnosing machines" (Ref. 11) must be applied in space medicine. The determination of the condition, or more correctly the syndromes, as a collection of individual deviations called symptoms, lies at the basis of any diagnostic process. /5

The development of diagnostic algorithms and corresponding machine programs is aimed at creating effective diagnostic automatic systems on a spacecraft. A diagnostic algorithm represents a strict instruction regarding the order of operation to be followed in decoding, analyzing, and evaluating medical information. The processing of information on the state of the cosmonaut, resulting in decisions relating to the safety of the flight, can be effective only with specific algorithms, independently of whether it is performed automatically or manually, on earth or on-board the spacecraft. Three groups of algorithms can be distinguished: determinant, probable, and self-changing (Ref. 12). Determinant diagnostic algorithms of a matrix type can be constructed today, on the basis of the information which we have on the reaction of the human being to the effect of different extreme factors, and on the basis of the experience accumulated from brief space-flights. As a result of studying the chemical models, the disturbances which are possible in a prolonged flight, and as a result of a theoretical analysis of prolonged-flight conditions, we can now develop more effective probable algorithms. Such algorithms make it possible to increase greatly the quality of decisions when there is an increase in the volume of input information (we have in mind here the collection of additional data by means of a system of medical studies).

Finally, the most up-to-date algorithms are the self-changing ones, which can increase their effectiveness over a period of time. The self-improvement of the algorithms is caused by the ability of the systems to accumulate information and by the presence of certain general principles which were provided for previously in the primary algorithm.

One very important problem for the programming of on-board diagnostic systems is the determination of the volume of input information which is minimally necessary for realizing the specified algorithms. The necessity of a minimum of input data is due primarily to the specific conditions of space flight. The term minimum input data designates the minimum recorders on the cosmonaut, the minimum electronic equipment on-board, and the minimum fuel requirements. However, this does not mean that reliability of "diagnosis" must be sacrificed for purposes of satisfying rigid engineering requirements. An on-board computer makes it possible to examine this problem from several aspects - from the aspect of fighting an excess of information and of extracting the maximum amount of useful data with the minimum amount of input data.

The construction of effective diagnostic algorithms , based on pro- /6 cessing minimum amounts of input information, requires an extensive analysis of the mechanisms controlling the physiological functions and a qualification of the correlations existing in the body between different physiological functions and their indices. A cybernetic approach towards studying the mechanisms by which the body is controlled makes it possible to introduce a quantitative interpretation of several phenomena which had only qualitative characteristics up to the present time. The systems of the human body are simultaneously concerned with an enormous number of controlling parameters. The homeostatic maintenance of uniformity in the internal medium and continuous dynamic balancing with the external medium are characteristic for the entire system. The human body is a complex, multi-purpose hierarchical system which consists of components which are subordinate to an organized purpose, so that the qualitative differences between the orders of discipline which arise consecutively create a definite sphericity in each of the levels. The interactions between the lower and upper levels in a complex biocybernetic system is based on the exchange of information according to the principle of feedbacks with controllable thresholds. Autonomy is characteristic for the lower levels at certain boundaries. Let us examine a simplified model of a two-component biological system, in which one of the elements is subordinated to the other. We can use the following as such an element: cell, organ, physiological system. An element in the lower level has the properties of self control, self regulation, self direction. These properties comprise the basis of any living system (Ref. 13). In order to achieve them, this element in the living system must have the necessary apparatus: mechanisms for receiving and processing information, control mechanisms which can formulate the appropriate commands, and effector elements which can realize them. The element under consideration must receive information both regarding the external and regarding the internal medium, and its reaction must be directed both externally and internally. The second component in the system, which is higher than the one mentioned above, is connected with it by means of channels of direct connection and feedback. The latter serves the purpose of control. Apparently, during the normal operation of the system, information is not passed along the feedback channel. Otherwise, the upper levels would suffer from an overload of information. Recent studies in the field of the physiology of reticular information has confirmed the fact that the principle of selective collection of only the most important signals is characteristic for control systems in a living body, even at the level of the cerebral cortex. Only if the lower element in the system cannot cope with the stream of information, or cannot separate the useful information from noise, do the elements in the upper level interfere in its operation. The interference of the upper levels in the operation of the lower level occurs in those cases when the body, as a complete system, is required to develop reactions /7 which keep it from destruction under the effect of unfavorable factors.

In this way the mechanisms in the upper level retain their high functional properties, due to the extreme effort of the lower levels.

By way of an example, let us examine the compensating-adapting reactions of the body to the effect of overloading (active portion of the flight). The existing experimental data allow us to distinguish two levels in the compensation mechanisms: a critical-somatic level and a vegetative level. As is known, throughout all of the space-flights, during the active portion of the flight the cosmonauts were completely conscious, turned on communications, fulfilled the required measurement acts, and adequately evaluated the surroundings. At the same time, several clearly-expressed changes were noted in the blood circulation, respiration, and metabolism systems. The activity of these systems was unusually intensified. A distortion was noted in certain reflex actions. Thus, when the pressure increases in the small circulatory system, it is known that there is a discharge reflex in the form of bradycardia, a drop in the arterial pressure in the large circulatory system, and a depositing of blood in the spleen (the Parin reflex, Ref. 14). However, with transverse accelerations, an "adequate" response is retained only in the spleen. According to existing data, transverse overloads of 8-12 units produce clearly-expressed dystrophic changes in the spleen of a dog, with the formation of thrombosis and disturbance of the trabeculae, which may be the result of the spleen overflowing with blood (Ref. 15, 16).

As is known, under the influence of overloading the arterial pressure increases, and the pulse rate increases. A blocking of the reflex from pulmonary vessels in the large circulation system can be explained by the simultaneous appearance of sympathins in the blood which has a hypertensive and positive inotropic effect. In this way the cortical mechanisms predominate over the vegetative mechanisms, and suppress those reactions which do not correspond to the over-all direction of the response of the entire body.

This example shows that it is impossible to construct a diagnostic algorithm by starting only with a selection of symptoms which comprise a certain syndrome. Under the specific conditions of spaceflight, new syndromes are formed, and in order to correctly evaluate them it is necessary to know certain general principles underlying the organization and operation of the biological systems. As was shown, one of the basic principles underlying the organization of such systems lies in the creation of a multi-level structure, in which the lower levels are subordinated to the upper levels, with each of them having autonomous properties.

Let us now examine an important functional indication of biological systems - their operational regime. All of the conditions of the body can be reduced to stationary and transitional conditions. /8
The stationary conditions are conditions of relative homeostasis, when individual components in the system are balanced with each other and with the external medium. Autonomous properties in each of the functional levels (physiological systems) thus appear to the greatest extent. The transitional conditions represent the reaction of the entire body or its individual components to disturbances (external or internal). Subordinational properties thus appear to the greatest extent in the components of the biological system, because a protective reaction of the entire body is both necessary and expedient in the given case. Since the transitional and stationary states imply a differing degree of constellation for the individual components in

the biological system, it must be assumed that the indices for the the intercorrelation of the different parameters of the physiological functions and the indices for the internal correlation in dynamic value sequences for one parameter will be different. Thus, the appropriate mathematical procedures can be developed for "diagnosing" stationary and transitional conditions of the body. For this purpose, it is necessary to employ the physiological meaning of such mathematical indices as depression, auto- and intercorrelation functions, distribution series, differential equations, etc.

At the present time, the positive results derived from applying correlation and spectral analysis to electro-encephalography are well-known (Ref. 17, 18). Data have been published on the physiological determination of several statistical indices obtained by analyzing the pulse rate of cosmonauts (Ref. 19, 20). We shall present an example of employing the histographic method for the purpose of studying the phenomenon of clearly-expressed fluctuations in the rhythm of cardiac contractions under conditions of weightlessness. There was significant intensification of the phasic sinus arrhythmia during an orbital flight during experiments with animals and during the first human flights (Ref. 21). A special statistical short study showed that an intensification of the phasic sinus arrhythmia is the result of the relative predominance of the tonus of the parasympathetic section of the vegetative nervous system, arising as a response to a decrease in the energy processes in the body and a decrease in the afferent impulse (Ref. 22). A histographic method was employed to provide a more detailed determination

of the role of phasic sinus arrhythmia in the reactions of the body to the conditions of weightlessness. A histogram (interval of 0.05 seconds) was constructed on the basis of values from 100-150 consecutive measurements. The histogram or the variation curve was characterized by three criteria: the position on the abscissa axis, width, and form. Laboratory studies showed that the variation curves for conditions of relative rest (stationary process) are characterized by a mean position on the abscissa axis, the width is determined within the limits of 0.20 - 0.35 seconds, and the curves for the form have a single peak and are compact. Variation curves of another type were recorded: curves extending up to 0.50 seconds, shifted to the right, and sometimes having two peaks. Transitional processes yield /9
asymmetric curves, which are shifted to the left and which frequently have several peaks. Under spaceflight conditions, four types of variation curves were determined, which corresponded to the flight periods as a whole.

In the pre-launch period, during the lift-off, and during the first revolution curves were recorded which were shifted to the left, were constricted, and had a sharp peak. These curves pointed to a high degree of interconnection between the pace maker and the central nervous system (sympathetic effect). During the first five-seven revolutions, the variation curves gradually took on the customary form and a mean position. Beginning with the second day of flight, the variation curves displayed a shift to the right, a widening, and the appearance of multiple peaks. These changes can be interpreted as the effect of the gradual predominance of the parasympathetic influences over the sympathetic influences, and as a decrease in the central control. Finally, on the third - fourth day of flight variation curves of a very specific type were noted: widened up to 0.8 - 0.9 seconds, with a great number of peaks, and flattened. This was apparently the result of autonomous control over the rhythm of the cardiac contractions by one of the lower controlling elements, without a noticable participation of the central mechanisms.

These data show that it is possible to develop a diagnostic algorithm for appraising the condition of the central control over the circulation system on the basis of only one parameter - pulse rate. Problems encompassing the extraction of maximum information from a minimum of data are extremely important in constructing effective diagnostic algorithms for programming on-board computers. Mathematical transformations of a very unusual type must be employed in such algorithms: a dispersion and correlation analysis, the formulation of distribution curves and differential equations, methods entailed in an information theory and game theory, etc. The utilization of cybernetic conceptions, along with mathematical methods, for interpreting data is very promising. Thus, the main possibility is thus opened up of determining single indices with respect to other indices, based on the inter-correlation of physiological functions. The largest correlation dependences will apparently be observed during the periods of extreme influences, when the degree of constellation increases in the control systems of the body. It is possible that the functional condition of individual systems can be evaluated with greater effectiveness by means of the degree of internal constellation of several parameters, than by means of their absolute values.

In conclusion, we would like to present the results derived from analyzing a seismocardiogram which represents a possible approach toward determining the degree of internal constellation of mechanisms in the intracardiac hemodynamics when one parameter is recorded in all. As is known, seismocardiography is a new method for studying the contracting function of the heart. It was first applied on Soviet /10 spacecrafts, and has now become a compulsory method in medical control systems in astronautics, and has been successfully applied in clinics for studying patients (Ref. 23, 24). The seismocardiogram presents a picture of the pulse rate, force and coordination of the cardiac contractions, and the characteristics of the intracardiac hemodynamics - particularly, the small circulation system. An analysis of the respiratory variations in these indices makes it possible to determine phase shifts between them. In our opinion, these phase shifts characterize the degree of internal constellation of the circulation system parameters. Indices of intercorrelation can be used for this purpose.

We have devoted a large portion of this report to examining problems related to the construction of effective diagnostic algorithms on the basis of processing a limited amount of physiological data. We demonstrated the manner in which the application of several cybernetic constructions to a description of the control mechanisms in physiological functions makes it possible to achieve practical results, in the form of specific mathematical methods of processing the data. In connection with on-board computers, the problem of collecting diagnostic information under spaceflight conditions can only be solved with effective diagnostic algorithms. The development of such algorithms has a direct relationship with the safety of prolonged spaceflights covering a great distance. It can thus be stated that two, comparatively new scientific disciplines - medical cybernetics and space medicine - have united forces in a field which is of great interest not only for present-day astronautics and future space studies, but also for practical medicine, because there is no doubt that achievements in the conquest of space can and must be used in the interests of humanity as a whole.

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